ATTACHMENT

Lawrence Livermore National Laboratory
California Energy Systems for the 21st Century
Illustrative Use Cases

1. Introduction

California has adopted several environmental and energy policy goals, including the Clean Energy Plan[1] aimed at:

- Reducing greenhouse gas (GHG) emissions to 1990 levels by 2020 and to 20% of 1990 levels by 2050.
- Increasing energy efficiency programs, targeting additional reductions of 5,000 to 8,000 MW of peak electricity demand.
- Supplying 33% of electricity sales with renewable electricity supplies, which will require about 20,000 additional MW of intermittent wind and solar resources.
- Promoting distributed generation technologies, including the California Solar Initiative and Small Generator Incentive Program, targeting an additional 5,000 MW of solar photovoltaic supplies and combined heat and power (CHP) plants.
- Retiring, replacing, and/or mitigating once-through cooling (OTC) power plants, which could affect over 16,000 MW of thermal resources by 2020.

While providing environmental benefits and introducing new sources of energy, the Clean Energy Plan presents new challenges to planners and operators of the electricity grid because the resulting supply and demand-side resources are not readily controllable. The reliable operation of the electricity grid requires system operators to continually adjust supplies to match demand, in order to maintain frequency within a narrow range around 60 cycles per second or Hertz (Hz). Instead of helping operators to adjust supplies to match demand, a new fleet of intermittent generation resources designed to meet California's energy and environmental policy objectives increases the need for greater operating flexibility. The increased reliance on intermittent resources also changes the use of existing resources, requires newer, more flexible resources to provide increased flexibility requirements, increases the uncertainty of market prices for energy,

[1] See California Clean Energy Future Overview prepared by California Air Resources Board, California Public Utilities Commission, California Energy Commission and California Environmental Protection Agency and the CAISO at http://www.cacleanenergyfuture.org.

reliability and resource adequacy services, and increases the need for ancillary services to integrate these resources.

The need for advanced operational understanding of California's energy delivery systems is not limited to the electric grid. More rigorous and flexible tools can help utilities develop strategies to reduce the risks and uncertainties associated with aging gas pipeline infrastructure and support the increasing need for real-time analysis.

In the corresponding application, the three investor owned utilities (IOUs) and the Lawrence Livermore National Laboratory (LLNL) propose an agreement for the "California Energy Systems for the 21st Century Project"(CES-21 Project) with the goals of providing the tools, analysis, and training to guide and manage this transition of California's power and natural gas system. The illustrative use cases presented in this document that describe the capabilities of the CES-21 Project are centered around four main areas:

- Electric Resource Planning
- Electric and Gas System Operations
- Cyber Security
- Workforce Preparedness

The following describes illustrative examples of potential work that the CES-21 Project may consider to undertake in Planning, Operations, and Cyber Security. The examples below define high-level, utility issues that have not been fully solved with conventional computing resources. These examples are preliminary and would be subject to further development, review and approval by the Project Board of Directors as part of the CES-21 Project's overall strategic plan, budgets and work orders. Workforce Preparedness would be addressed in each area as appropriate as the work progresses. The IOUs and LLNL anticipate that the mutual working relationship will foster the technology transfer to assist the utilities in preparing to meet the challenging issues facing the energy utility industry in the 21st century.

2. Planning Use Cases

These examples focus on two key areas in planning: 1) improved electric resource planning tools; and 2) metrics to reflect the changing grid dynamics introduced by intermittent resources.

2.1 Improved Electric Resource Planning Tools

Research Objectives & Benefits

Utilities currently use commercial off-the-shelf (e.g. PLEXOS) and in-house developed modeling tools for planning to integrate increasing renewable resources. For daily dispatch of resources, the utilities use hydro-thermal optimization and unit commitment models with simplified representations of the electric system and uncertainty variables such as weather, customer demand load and participation of generation in competitive California Independent System Operator (CAISO) markets. Increased participation of variable generation in CAISO markets, in the quantities contemplated by California's Clean Energy Plan, will make CAISO and utilities planning and operations increasingly complex. For many urgent and longer-term planning and policy questions, these models are computationally limited in their ability to represent the complexity of the electric grid, the time-scale of key generation resources and transmission assets, or the responsiveness of electrical storage. It is very time consuming to run multiple scenarios of some of these existing planning models.

Additionally, existing modeling methods do not fully capture the operational characteristics and capabilities of existing resources. The model is not dynamic so it does not address and provide multiple solutions to issues posed by OTC related closures, bulk power constraints, new generation, new transmission, and increased distributed generation penetration. Further, transmission reliability and voltage issues are not taken into account in renewable integration analysis.

Because of the time it takes to run these models, it is not uncommon to use an aggregated model. But even a model that represents the Western Electricity Coordinating Council (WECC) as 40 nodes and uses one hour time steps takes many hours to run. This means that typical analyses are done using only a limited number of use cases, thereby increasing the chances of error. Higher resolution representations of the transmission system (1,000 or the full 15,000 nodes) looking out over a year would require months or more to complete a simulation usable for analysis. Also, if the time step in these simulations were reduced to sub-minutes, this would also greatly increase the computing requirements. Such computational bottlenecks require improvements to optimization algorithms and the appropriate application of High Performance Computing (HPC). The CES-21 Project could address the need for incorporating more transmission lines into the simulation and higher time resolution that will take into account integrating the dynamics of wind and solar.

New or augmented tools need to be created to meet California's ability to integrate the growing fleet of renewable resources. Through CES-21 Project, stakeholders will gain a better understanding of the capabilities and limitations of the current modeling tools and have a forum to collaborate on the development of new tools. The CES-21 Project will augment the functionality of existing models to better represent the complexity and responsiveness of the grid, as well as the scope and parameters of possible scenarios. This approach will speed up the incorporation of advanced tools into the decision-making process and operations of the three IOUs.

Studies using different load and resource portfolios (e.g., different levels of intermittent resource penetration and technology mix) and system conditions are needed to develop recommended planning and operating guidelines. Some progress has been made to estimate incremental needs for integration requirements for a limited set of scenarios. In particular, the CAISO in collaboration with the three IOUs, Energy + Environmental Economics (E3) and PLEXOS have conducted modeling in the context of the CPUC's Long Term Procurement Plan (LTPP) proceeding to assess the integration of renewable resources into California's supply portfolio. However, these analyses have been inconclusive. New tools are needed to model seasonal and daily economic dispatch of resources in a more complex environment with variable and uncertain generation.

Description of Research

In order to model the complexity of California's electric system, new tools are need to balance reliability, costs, and regulatory limitations (e.g., GHG emissions), as well as transmission capabilities, economic use of supply, demand-side resources, distributed generation, and storage under uncertain system and market conditions. The increased reliance on intermittent generation requires planners and operators to use resources differently in the future than they do today. For example, existing gas-fired generation will be required to start-up and shut-down more frequently and to operate at lower power output levels more frequently than they do today to accommodate increasing levels of intermittent generation. Similarly, hydro resources will be used differently to accommodate variable and more uncertain wind and solar production. The system of the future will need to take advantage of flexible demand to shape its consumption based on available resources and to provide more ancillary services to integrate renewable resources.

In some cases, existing tools cannot represent important aspects of a problem (e.g., how people may choose to purchase, drive, and charge plug-in vehicles). In other cases, new questions are in the earliest stages of consideration (e.g., the physics and costs of cascading failures caused by cyber-attacks on smart meters). As directed by the CES-21 Project, the team of investigators will create new tools and representations of problems to face emerging concerns. Examples of these tools include:

(1) Unit commitment modeling for hydro-thermal optimization which recognizes the residual value of limited energy resources over multi-month periods. Most current tools are restricted to optimizing over a shorter period of time (e.g. 1 week). This limitation creates a sub-optimal solution.

(2) Improved simulation models of unit commitment for optimization of bid parameters. Detailed models provide more accurate results and therefore creating an optimal solution.

(3) Stochastic short-term unit commitment considering renewable resources, load forecast, and market uncertainties. Most simulation tools require deterministic assumptions to

reduce the complexity of the simulation. However, highly random and intermittent resources require a stochastic approach to accurately model system behavior.

(4) Storage modeling. There are limited modeling tools that account for the complexity and market opportunities provided by storage. Additional models are required to accurately determine the value of storage.

(5) Methodologies to forecast the effects of dynamic pricing, demand response, and bidding disaggregated load into CAISO's markets. Currently, there are limited tools and methodologies for modeling market behavior and customer response to market dynamics.

(6) Improved models to enhance day-ahead estimates of wind power production to reduce energy and ancillary services costs for the CAISO market.

<u>CES-21 Project Role</u>

The CES-21 Project proposes to augment existing models and develop new analytical tools to operate the electric system as envisioned by California's energy and environmental policies, including its Clean Energy Plan. New tools are needed to make economic and efficient use of both demand- and supply-side alternatives for the benefits of California's electric consumers. The California energy system will benefit most from these augmented and new tools when the IOUs understand their use and functionality into its planning and operations. A central plank of the CES-21 Project's work scope is to train new and existing utility staff in the effective use of new modeling tools in planning, operations, and infrastructure protection.

2.2 Flexibility Metrics and Standards

Research Objectives & Benefits

New flexibility metrics are needed to operate the state's future electricity grid in a secure and flexible way to ensure that the State's Clean Energy Plan is operationally feasible, and to help design robust energy and ancillary service markets. Given the planned increase in intermittent renewable resources, the electric grid needs to be more responsive and flexible than it is today. However, current planning and operating guidelines do not consider the grid's operating flexibility needs, especially in the context of increased intermittency.

The CES-21 Project proposes to develop flexibility metrics and standards to guide the planning and operation of California's electric grid in a future where a large portion of the state's electric supply is provided by resources that offer little or no operating flexibility. Specifically, this proposal would build on efforts by the North American Electric Reliability Corporation (NERC),[2] the Western Electricity Coordinating Council (WECC)[3], the Lawrence Berkeley National Laboratory (LBNL), the CAISO, and others to consider the needs of the entire system in the face of changing policy, climate, and technology.

A metric is a unit of measurement. Just as when measuring speed we use miles per hour as a metric, planners and operators utilize metrics to measure the grid's operating flexibility. Operating flexibility is the ability of the grid to adjust to changing conditions ranging from the loss of major generation or transmission facilities to large variations in demand and supply from intermittent generators. In addition to developing new flexibility metrics, the CES-21 Project will also utilize standard reliability, efficiency, and environmental impact metrics when using simulation, optimization, and other analysis models to evaluate the performance of the electric system under different scenarios. The new tools developed will help determine which metrics can best evaluate and determine system needs and requirements. These metrics can then be

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[2] See NERC's *Special Report on Flexibility Requirements and Metrics for Variable Generation: Implications for Planning Studies*, August 2010 Draft. The report can be found at: http://www.nerc.com/docs/pc/ivgtf/IVGTF_Task_1_4_Final.pdf.

[3] In October 2008, WECC established the Variable Generation Subcommittee (VGS) reporting to the Joint Guidance Committee (JGC) to identify issues and opportunities related to presence of variable generation sources in the Western Interconnection and facilitate the development and implementation of solutions that add distinct value to WECC members. The VGS focuses on the regional reliability and market challenges of renewable energy integration and other emerging issues as requested by the JGC.

adjusted or changed as necessary.

Today, California's electric grid uses loss of load expectation (LOLE), planning reserve margin (PRM), and operating reserve margin (ORM) as key reliability metrics. These metrics have corresponding targets or standards that serve as guidelines for electric resource planning and reliable operations. Figure 1 shows the current operating and planning metrics and targets.

Figure 1: Current operating and planning metrics and targets

Metrics	Targets
LOLE (Loss of load expectation) % probability of outages	1 day in 10 year expected outage
PRM (Planning Reserve Margin) Excess resources above peak load, expressed as % of peak load	15% to 17% PRM
Contingency Reserves Excess resources above peak load, expressed as % of peak load	About 6-7% (Spinning and Non-spinning Reserves)

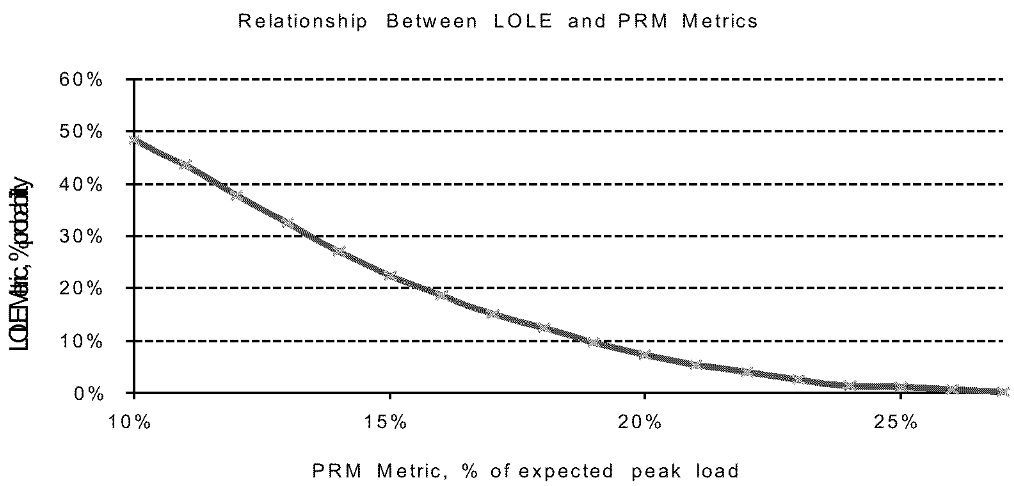
(1) LOLE Metric

The LOLE metric measures the probability of interruptions to customer service due to insufficient supply. The typical LOLE target is used in the electric industry to maintain the likelihood of customer outages due to supply deficiencies below a 1 day in 10 year LOLE target; that is equivalent to a 10% chance of supply deficiency outages in a year. This target depends on the policymaker's risk preferences. Customers also have different LOLE preferences, with industrial customers who depend on processes that require higher reliability wanting lower LOLE targets, or lower chances of curtailment, than residential customers.

(2) PRM Metric

The PRM metric defines the margin or excess resources the grid has above its expected peak load. To meet the 1 day in 10 year LOLE target, California has adopted a 15% to 17% PRM target as part of the CPUC's Resource Adequacy (RA) program. Figure 2 shows an illustration of the relationship between the LOLE metric and the PRM metric. Higher PRM reduces LOLE.

Figure 2: LOLE and PRM Metrics – Illustration



The RA program requires load serving entities (LSE) to procure sufficient qualified capacity (supply or demand-side capacity) in the planning timeframe (i.e., before the start of the operating year or month) equal to or higher than the LSE's expected peak demand plus a PRM of 15% to 17%. In concept, the PRM target ensures that sufficient resources are available at the start of the operating year to cover resource outages and increases in peak demand due to above expected summer temperatures, while leaving sufficient resources available to cover minimum ORM requirements.

(3) Contingency Reserve Metric

At the start of an operating day, the CAISO is required to have a minimum amount of Spinning Reserve and Non-Spinning Reserve[4] (at least half of which must be Spinning Reserve), sufficient to meet the NERC Disturbance Control Standard BAL-002-0, equal to the greater of:

a) The loss of generating capacity due to forced outages of generation or transmission equipment that would result from the most severe single contingency; or

b) The sum of five percent of the load responsibility served by hydro generation and seven percent of the load responsibility served by thermal generation.

Description of Research

Current reliability metrics and targets were developed for an electric grid that did not have as much non-dispatchable and intermittent resources as the future grid envisioned by California's Clean Energy Plan. The metrics that have historically been used to monitor and ensure stable electric grid operations were designed in a different era. They do not capture the range and diversity of available control mechanisms that would be present on the grid of the future, nor do they capture the inherent variability of new intermittent generation sources and load changes. Thus, metrics that capture this future state and provide a broader scope of control options are needed.

The need for operationally flexible capacity (supply- or demand-side) will depend on the characteristics of the electricity portfolio, including:

- System inertia
- Variability and forecast uncertainty of electricity demand and variable electricity supplies

[4] WECC's Operating Reserve requirements for the Western Interconnection (BAL-STD-002-0).

- Correlation between variability of demand and supply

There may be no simple "one size fits all" capacity level metric analogous to today's PRM that addresses these issues. Instead, the new metrics might capture the relationship between the amount of flexible capacity available to a system and the degree of variability and forecast uncertainty of that system's combined load and variable generation. There is a need to update planning criteria, not only to integrate intermittent renewable resources, but also for potential increases in demand fluctuations due to the deployment of new demand response programs and the system's increased reliance on load shedding from price-sensitive customers using smart meters.

The following three additional performance metrics should be considered when analyzing alternative grid architectures, along with others to be determined at a later time and potentially based on the outcomes from the new tools.

(1) Frequency Response Ratio

This metric would define the frequency-responsive capacity the system needs to respond rapidly in a matter of seconds to major losses of generation or transmission facilities to keep frequency changes within preset bounds and avoid undesirable customer outages. This frequency response metric would most likely apply at short time scales, for instance in the first few seconds following a major contingency. The desired standard for meeting this frequency response metric would include fast acting storage, demand response, and other types of supply- and demand-side frequency response along with the inherent inertial response already on the grid.

(2) Regulation Ratio

This metric would define the flexible capacity on automatic generation control (AGC) that the system needs to respond to variability and forecast uncertainty of net load within five to ten minutes. Net load is the residual load left after subtracting intermittent wind, solar and other variable and uncontrollable generation. This regulation metric would most likely apply at five to ten minute intervals, and would help identify AGC responsive capacity, supply or demand-side capacity, to meet a selected regulation standard.

(3) Load Following Ratio

This metric would define the additional flexible capacity that the system needs to respond to variability and forecast uncertainty of net load within the operating day (intra-day and intra-hourly), which is not already covered by the Frequency Response or Regulation metrics. This load following metric would identify needs for flexible capacity that can be re-dispatched or started within minutes to manage the remaining operating variability and forecast uncertainty not covered by frequency and AGC responsive capacity. Sources of flexible capacity to satisfy a selected load following standard will also include supply- and demand-side alternatives.

In addition to the existing reliability metrics explained above, the CES-21 Project will also utilize standard cost and environmental impact metrics to evaluate the performance of the electric system under different scenarios.

CES-21 Project Role

The CES-21 Project proposes to develop new flexibility metrics and standards to guide the planning and operation of the future electric grid. This use case presents several examples of possible metrics, and standards that the CES-21 Project proposes to develop to ensure the reliable and efficient operation of the future electric grid. New flexibility metrics are needed to help design energy and ancillary service markets, and to operate the state's electricity grid in a secure and flexible way to ensure that the State's Clean Energy Plan is operationally feasible. Results from the CES-21 Project can help inform California about what initiatives may be needed to reliably operate the State's electric system under the State's Clean Energy Plan, which may include new flexible generation, new market products, and/or regulatory and policy changes.

3. Electric System Monitoring and Control

Research Objectives & Benefits

One of key operational issues faced by California utilities is the ability to manage intermittent resources effectively while utilizing grid assets efficiently. This has historically been done through centralized collection of field data monitored by various operational entities (e.g. regional coordinators, balancing authorities, and transmission providers) with support from operational engineering personnel. It has also been accomplished using generation resources with fairly predictable and controllable output. Even in this very mature generation mix, instability and system wide outages occur on a periodic basis. With the increasing amounts of intermittent resources, stability analysis becomes more critical than ever to understand the possible issues and to develop mitigation plans.

The health of the system is studied and monitored for 1) future events like line maintenance and generator outages; 2) real-time monitoring; and 3) post-analysis to discover root causes of significant system events. This leads to a tremendous amount of system data that is created, processed, and analyzed. While there are useful tools and computing analysis software, much of the data is recorded but not collected in any single system that could analyze the data holistically for trends or indicators of system stress. This example describes possible methods to monitor and control the bulk power system and methods to increase the analytical capabilities of the utilities.

The potential benefits from this use case include:

- Improved monitoring capability and system dynamics understanding to reduce overall system outages through early warning and mitigation plans
- Reduced generation and load dropping on special protection schemes
- Increased wide area system awareness and understanding to increase transmission capacity

- More detailed modeling capabilities and longer dynamic analysis to increase overall understanding of interplay between transmission and distribution systems with substantial amounts of intermittent generation

Description of Research

There are four key work streams that would be investigated as part of this research.

Situational Awareness

The situational work stream involves data mining to create a predictive algorithm to identify system stress and determine notifications/alarms to transmission and system operators.

All western state utilities have extensive power system data. This data includes for most utilities:

- Sub-second data from phasor measurement units (PMUs)
- Sub-second detailed event data from digital fault recorders (DFRs)
- Periodic (every 2-4 seconds) data on transmission line loading indicating transmission status and generation injection

This data is used to manage the power system and to perform detailed analysis for specific events (e.g. unusual system faults). Due to the vast amount of data in dissimilar data formats, there has not been an opportunity to fully leverage this data within a utility nor is data shared across utilities except in investigations of unusual events.

The data for each device/system is described briefly:

- PMU data – This data is collected every two cycles (thirty reads/second) at major bulk power system substations and include voltage, current, phase angle, and frequency. The data is continuous and creates a 5MB file every three minutes.
- DFR data – This data is generated on each fault incident on the bulk electric transmission system and contains detailed information on the characteristics through the interruption of the fault.
- Energy Management System (EMS) – This data is from the Supervisory Control and Data Acquisition (SCADA) system that provides transmission power flow, bus voltage, and circuit breaker status for the entire transmission system.

The computing resources have not been available to analyze and correlate this data to determine specific rules that could be mined from comparing the sub-second synchrophasor data to the data collected on the transmission system (e.g. SCADA data that reflects the operating conditions of the transmission and distribution system). Considerable computational effort would be needed to correlate the sub-second data with the second-by-second data, along with historical events on the system. Correlations of this data could prove to predictive indicators for system operators, enabling a real-time awareness. Pattern recognition algorithms and multivariate time series models could also be developed to provide predictive capability. These predictive indicators would then be used in the Western Interconnection Synchrophasor Program (WISP) currently being developed with the Western Electricity Coordinating Council (WECC) and many of the western states IOUs as well as Federal Power Marketers.

This predictive information would derive the alarms that would notify the system operator of the current power system situation. These alarms would provide the basis for the visualization system envisioned in the WISP initiative.

The correlation between the synchrophasor data and system events could also be used to compare results derived from load flow, stability, and electromagnetic transient software systems like the Real-Time Digital Simulator (RTDS), Positive Sequence Load Flow (PSLF), and PSCAD/EMTDC to validate model accuracy across all major software tools. In addition to assessing the correlation between PMU signals and system faults, high fidelity real time models can be used to study the circumstances that give rise to the PMU signatures and subsequently to the faults. A better understanding of the mechanisms that give rise to the PMU signatures may enable additional alerts for impending failures.

These studies can be conducted on generalized high performance computers or on specialized computers such as the RTDS. The process would seek out the characteristics of circumstances that could lead to a given signature. If, for example, only one circumstance can be found that gives rise to a given signature, the signature can be considered diagnostic of that circumstance. However, if more than one circumstance gives rise to similar signatures we can assess the probability that the signature signals identify a type of circumstance. Since each individual signal will not be identical, we may be able to train pattern recognition software to better identify the underlying causes of the signals.

Adaptive Protection

The adaptive protection work stream would involve using system stress as an input to special protection schemes to more accurately design the bulk power system to reduce generation dropping and load shedding

If the predictive algorithm is created and operationally found to be accurate and useful, the next step would be to use this predictive information to inform special protection systems. Currently special protection systems are used to allow generation interconnection under a set of special rules. The rules generally include some type of generation tripping or load shedding to be activated during certain contingencies (generally transmission line outages caused by a fault on the power system). The special protection system protects the overall system stability during the outage by reducing power flow through either generation and/or load tripping.

The variety of contingencies that result in arming (enabling a generator or load trip action to occur when a line outage occurs) and the amount of generation and/or load to drop are based on detailed studies using conservative standards to ensure a very stable system. If the predictive engine accurately measures the stability of the dynamic system, this engine could provide the input to these devices as opposed to the more conservative static determinants. This would mean that special protection schemes would generally be armed less often resulting in less generation and/or load tripping actions. The dynamic inputs could also determine the amount of generation and/or load tripping, consequently reducing the actual amounts required to trip.

Dynamic Transmission Path Capability

Under this work stream, researchers would use the dynamic stability state indicated by the predictive engine to determine transmission path capability based on actual system conditions as opposed to static ratings based on traditionally conservative assumptions.

If the first two phases were successful and there were direct benefits from the control approach on special protection systems, this would be a strong indication that a dynamic path capability program would also be successful. This would change the method of determining path capability again from the current static determination based on fairly conservative rules to a path capability determined dynamically by the current stability state of the system. The predictive algorithm would have to produce accurate and reliable information. Extensive testing of multiple scenarios would have to be employed with a very detailed and accurate system model to obtain the confidence in the results for this type of path capability system to be deployed. The application of these algorithms would also take agreement by the balancing authority and the regional reliability coordinator.

Improved Modeling and Analytics for Dynamic Stability Studies

The last work stream for this research area would involve creating more detailed models including components of the distribution system that are normally modeled using simple equivalents. Researchers would perform dynamic analysis on this more detailed model over longer periods of time to more accurately depict the dynamic nature of the transmission system with intermittent and distributed resources.

Dynamic analysis is constrained by the runtime of analysis and the model equivalents that are required. An HPC environment can overcome these situations. This would allow utilities to expand the timeframe of the analysis and the numbers of scenarios as well as analyzing a more detailed model that more accurately defines the power system.

CES-21 Project Role

As described above, while analysis is undertaken by each utility, The CES-21 Project would combine the problem defining capabilities within the utilities with the unique computing environment and expertise in parallel processing provided by Lawrence Livermore National Lab.

4. Natural Gas System Modeling

<u>Research Objectives & Benefits</u>

The IOUs currently model the gas backbone, transmissions and distribution systems with software platforms such as the SynerGEE hydraulics code developed by G. L. Noble Corporation. The code solves the nonlinear equations governing pressure drop over lines, compressor efficiency, pressure drops through valves, mass flow, and other phenomena to find the steady-state flows through all pipes in the system. For a given configuration of pressure set-points and compressor outputs for components in the system, this model serves as a function evaluator that returns all of the steady state flows in the network. These models are computationally intensive and take a significant amount of time and resources to run. The immediate business value is therefore to be able to run thousands of hydraulic scenarios without user intervention required for each scenario.

In addition, these models have known limitations which affect their flexibility and speed with which they can be manipulated even by the most skilled and experience gas planning engineers.

- The models require a high degree of manual intervention for functions that could be automated, significantly increasing the time needed to evaluate multiple scenarios. For example, geographical information systems (GIS) location information is not integral in the flow modeling software currently in use, and as such must be input manually to achieve a spatial model;
- Configuration management of model elements across the system is difficult, in part because there are multiple disparate models;
- Computational limitations prevent interconnection of multiple models and more detailed representations of gas pipeline segments and features such as valves is difficult; and
- The models must manually incorporate affects on gas demand patterns due to the addition of intermittent renewable power to the electric grid.

By improving the functionality, speed, and capabilities of the natural gas modeling platforms and the existing hydraulics code, the utilities will gain greater modeling speed, resolution, and fidelity. Every capability and upgrade that is added to the modeling platform used by the IOU's, whether introduced into commercial code through collaboration with the software vendor or developed independently by LLNL, tends to increase the computational complexity (e.g. requirements for I/O, data storage, and visualization). The CES-21 Project with LLNL and the HPC Innovation Center will ensure sufficiently powerful facilities are available to support these improvements.

Description of Research

Three types of improvements in this example could be used to improve the efficacy of gas pipeline modeling. These are discussed below.

Improve the efficiency and ease-of-use for existing third-party modeling software

This work would involve designing and building new interfaces, wrappers, and data management platforms for the existing natural gas models. These will greatly accelerate the ability to run models, and increase the accuracy and complexity they can represent.

These modeling upgrades will leverage and optimize the third-party software and proven computer code currently in use by the utilities, rather than reinventing new models and algorithms from scratch. LLNL and the utility teams will work with the vendors to improve their codes' operational capabilities and devise solutions and approaches tailored to the operational requirements and functional needs of the California (and eventually national) IOUs and regulators.

New approaches to optimization

To demonstrate the benefits of new optimization capabilities, the team would formulate and solve a series of optimization problems with HPC to provide more actionable information to decision makers more quickly. This will attempt to optimize price, risk, and emissions and help to foster a greater understanding of the complications and benefits to the utilities of this expanded capability.

An example of one such demonstration might be to model of PG&E's Sacramento local distribution network, which has 37 key pressure regulation points. The set-points of these pressure regulators and the power supplied to compressors would serve as the control variables in the optimization model. The demonstration might seek to minimize gas system operating pressures subject to specified pressures on identified segments, and winter customer demand scenarios.

In this example, operating costs are specified as the objective function. Other functions could be used, such as the weighted sum of pressures at the regulation points where larger weights and consequently greater importance could be assigned to sections of the system deemed to be at higher risk potential. Alternatively, the models could be optimized for volume of gas delivered to customers (in the event not all customers could be served).

These problems could be solved by implementing new non-linear optimization software that produce an array of scenarios and outputs using hundreds to thousands of runs from the SynerGEE model (used by PG&E). One challenge to the existing software is that in the SynerGEE third party software, multiple localized solutions are returned which may need to be resolved in order to find a system-wide optimal solution.

One solution to this modeling issue is to commence optimization runs at multiple points. An alternate approach would be to implement simplex-based non-linear optimization methods in order to efficiently explore the solution landscape. These robust optimization methods, although conceptually straightforward, may not be effectively supported by the existing conventional utility models but could be demonstrated and evaluated using HPC.

Existing utility modeling software would be used to estimate the pressure at all points in the system to ensure that none of the constraints on gas pressure and gas demand are violated. Advanced computing and optimization methods would be employed and evaluated against existing methods for speed of analysis, accuracy of results, ease of use, and flexibility for modeling scenarios.

Coupling natural gas and power network system models

Severe electric system ramp events, up or down, due to intermittent generation adds changing demands to the gas pipeline networks. While these events have not caused immediate problems, it is not clear how increased renewable loading may create operational challenges to the pipelines. It is also not clear how changes in the maximum allowable operating pressures (MAOPs) on gas pipelines supplying generators might affect operations as pipelines are being upgraded over the coming years. Connecting the gas and power network models together might provide a better understanding of how changes in power grid might affect the natural gas network and vice versa.

CES-21 Project Role

As described above, the CES-21 Project would combine the problem defining capabilities within the utilities with the extensive modeling and computational tools and expertise in parallel processing provided by LLNL.

5. Cyber Security

Research Objectives & Benefits

The overall objective of this research initiative is to help build a more resilient, reliable grid and to protect customer information privacy. It will help the IOUs, regulators and other stakeholders anticipate cyber security risks, drive research, influence standards, and develop the next generation tools and methodologies needed to continue to protect the grid from evolving and increasingly complex threats. This research is being proposed in response to a number of critical industry drivers and challenges:

- The world today hosts a variety of cyber security threat actors that are more sophisticated, well-funded, and persistent than ever before
- It is well known that IOUs and the critical infrastructure they support are significant targets.
- The grid's increasing interconnections and growing complexity is introducing new cyber vulnerabilities that need to be managed.

The CES-21 Project should enable the utilities to enhance their cyber security posture as new applications and technologies evolve and the grid becomes smarter, more interconnected, and more complex. Examples of deliverables from this research include:

- New cyber architecture solutions based on successful tests and lessons learned.
- New or augmented tools and processes to detect, prevent, respond, and recover the smart grid from cyber attacks
- Proposals for new standards to secure the smart gird
- New or refined methodologies and tools for testing and evaluating smart grid software and architectures

Description of Research

The main focus of the joint research effort will be on understanding the Smart Grid communication network, the threats to the network, and the prevention, response, and/or reaction to those threats. Some of the proposed work streams for this research include:

- Conducting vulnerability assessments of emerging Home Area Networking standards (after standards are developed)
- Understanding how different cyber security scenarios might affect applications such as Synchrophasor, Plug-in electric vehicle integration, renewable resources, equipment disruption and damage, and distribution automation
- Assessing risks associated with critical infrastructure interdependency to provide input to business resiliency planning
- Using advanced binary and source code analysis tools and methodologies to enhance the security quality of smart grid software

These and other research areas can be pursued by following a five-phase approach:

1. Situational Awareness of the Smart Grid infrastructure
2. A high level description of the Smart Grid information infrastructure and evaluation of the efficacy through controlled experiments in a testbed environment
3. Identify and Prioritize the Threat Environment and Threat Actors
4. Simulate Cyber Attacks
5. Identify Protective Tools, Processes, and Standards

Phase 1 – Situational Awareness

Develop a distributed, streaming analytics capability that can detect and identify cyber threats in real-time, thereby providing real-time smart grid network situational awareness. This system will utilize sensors at multiple locations instead of the "Maginot Line" philosophy that is now common. This configuration requires individual sensors to have only a limited window into the high-bandwidth, streaming network flow which decreases their complexity. These sensors must communicate with each other to gain insight into potentially anomalous behavior.

Phase 2 – A High-Level Description of the Smart Grid

Define a high level description of the smart grid network through the process of discovery and the identification of critical assets. This description should feature the long-term designed-in cyber security of the SCADA system, smart grid components at three levels: architecture, product/system, and intra-and inter-sector, including protection at extended perimeters, such as substations, smart meters, etc. Compare the as-built description against the as-designed specifications. Build a small test-bed laboratory to include representative hardware and software of the as-built infrastructure for the IOUs (e.g., to include smart meters). This laboratory would then be used to develop small-scale descriptions of networks and do penetration testing on real devices in a laboratory setting. This description of the smart grid network would then be informed through actual data from the existing infrastructure and from the test-bed. Finally, it will also be used for risk assessment, risk modeling, simulation, and the development of protective measures.

Phase 3 – Identify and Prioritize the Threat Environment and Threat Actors
Identify and prioritize the threat environment and threat actors. Threat actors include nation-states, terrorists, criminal elements, and insiders. Threat scenarios range from evolving malware and spyware to Advanced Persistent Threats (APTs). The threat scope includes physical, cyber, and combined. This understanding of the threat will be done in the context of the business functions that the application is supposed to perform, such as remote load curtailment or remote switching of distribution element. An element of this phase would be to perform penetration testing and vulnerability analysis informed by the description of the smart grid network developed in Phase 1. Penetration testing and vulnerability analysis in the test-bed laboratory is important for understanding the full threat surface possible to adversaries. Red Team exercises provide means to evaluate robustness of the threats to the infrastructure and help inform the designation of priority or threat.

Phase 4 – Simulate Cyber Attacks
Use prioritized threat scenarios from phase 3 and the description of the smart grid network from phase 2 to simulate cyber-attacks, impacts, and protective measures. Protective measures include detective, preventive, responsive and recovery mechanisms. The results and conclusions of attack simulation will be analyzed and reported. The above simulations will be leverage to design solutions that will ensure that each utility is able to achieve significantly better measures for detecting, reacting, and recovering from cyber-attacks. This also enhances each IOU's ability

to coordinate with each other to protect against global threats, including against APTs.

Phase 5 – Identify Tools, Processes & Standards

Using the results of the above steps, identify new or advanced tools, processes, and standards for enhancing security as the grid gets more interconnected and complex. These tools will be based on detecting anomalies as opposed to simple signature recognition. Anomalies will include both technical and behavioral. In addition, this initiative will identify approaches to continuously optimize, the proactive and predictive cyber security posture to deal with even more sophisticated, never seen (zero day) and hard to detect cyber threats. Where applicable, the CES-21 Project will develop suitable training necessary to enhance the technical caliber of IOU security practitioners.

CES-21 Project Role

The CES-21 Project will leverage the resources of national labs, academia, technology vendors, regulators, standards development organizations, IOUs, and other stakeholders to address increasingly important issues surrounding cyber security. In particular, the strengths of the national labs in modeling, simulation, and applied research will help the IOUs deal with some of these challenges. It is the expectation that this program will enable the utilities to enhance their cyber security posture as new applications and technologies evolve and the grid becomes smarter, more interconnected, and more complex.